The Kinematics of the SN 1987A Beam/Jet(s)

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Early measurements of SN 1987A indicate an intense beam of light and jet of particles which impacted polar ejecta (PE) remaining from the previous binary merger which formed Sk -69°202. The photon beam (aka "enhanced UV flash") scattered off/reprocessed in, without significantly penetrating, the PE, producing 2×10^{39} ergs/s for about a day at day 7.8, roughly consistent with the delay predicted from the 60 mas offset (17 light-days in projection) of the "Mystery Spot" (MS), and the ring/bipolar geometry. This scattered flux then decayed for a day with a timescale consistent with the UV flash, after which the luminosity rebounded above the day 7.8 value by day 9.8, and continued rising linearly with time, until a decrement of 8×10^{39} ergs/s occurred at day 20, indicating: (1) particles from the jet penetrating into, and eventually through, the PE, with (2) the fastest traveling at 0.9 c, (3) the distance from 87A to the PE was 11 ℓt-d, (4) its depth was 13-14 ℓt-d, (5) the BJ angle to the line of sight was 72 degrees, and (6) that both the enhanced flash and jet initially had collimation factors in excess of 10,000. The 45, 60, and 74 mas offsets of the MS at days 30, 38, and 50, indicate the eventual formation of a luminous plume from the less relativistic jet and PE material, initially traveling at ~0.5 c, but eventually decelerating to ~0.35 c. The pulsations (nearly always at ~ 2 ms) drive the bipolarity in SNe and produce gamma-ray bursts. Pulsar intensities drop only as 1/distance, and thus he superluminal polarization current model of H. Ardavan & Co. holds up.

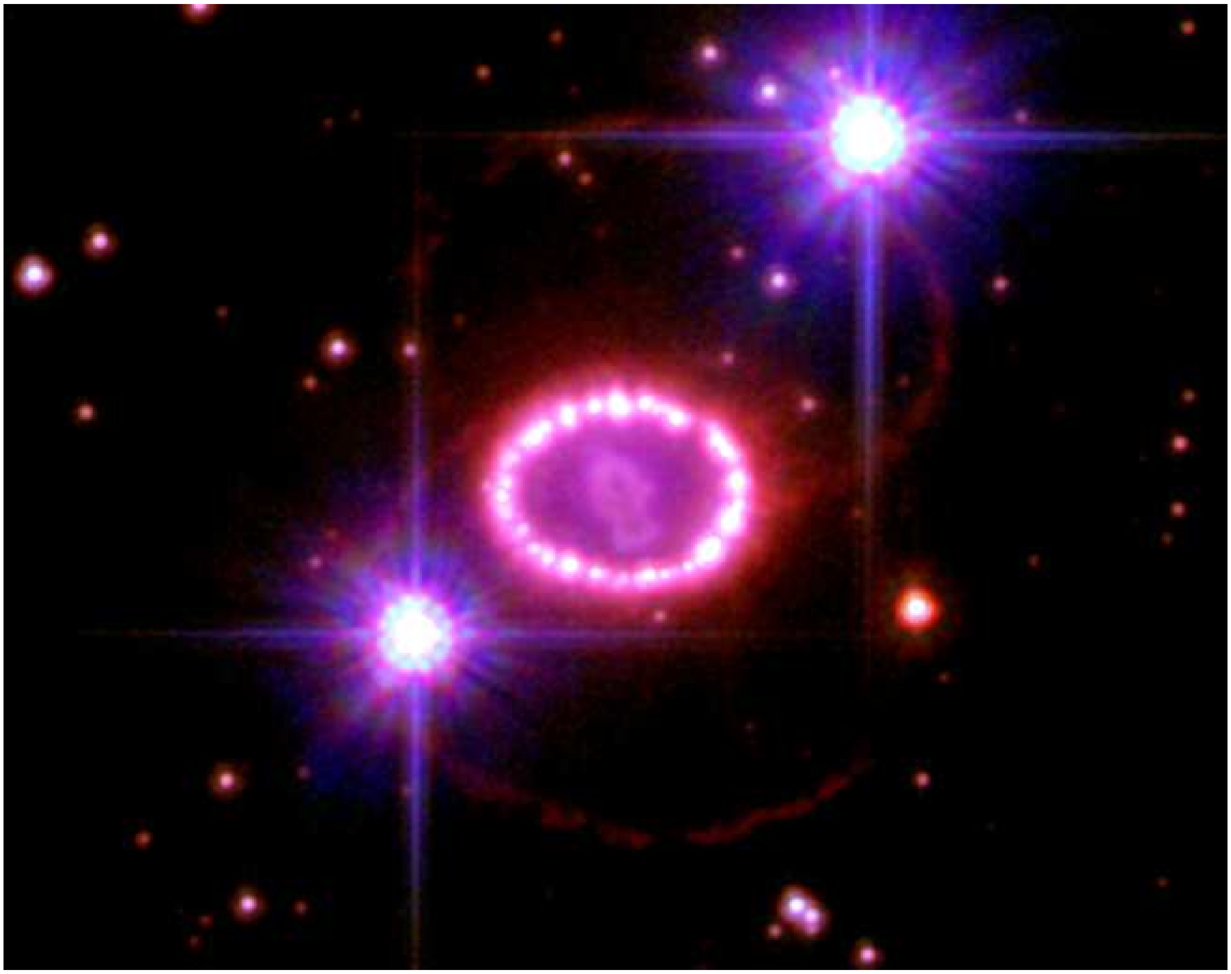

Fig. 1. SN 1987A as of December 2006, as viewed with the HST (NASA, P. Challis, & R. Kirshner, Harvard-Smithsonian Center for Astrophysics). North is up, east is to the left. The bipolarity of the explosion is suggestive of (electron) degenerate core-core merger-induced collapse ("Double Degenerate" – DD). The axis of the bipolarity corresponds to the "Mystery Spot" bearing of 194^{o} (the far-side [southern] minor axis of the equatorial ring has a bearing of 179^{o}). The pulsar within this remnant (and all other remnants as well) caused this bipolarity (see further below).

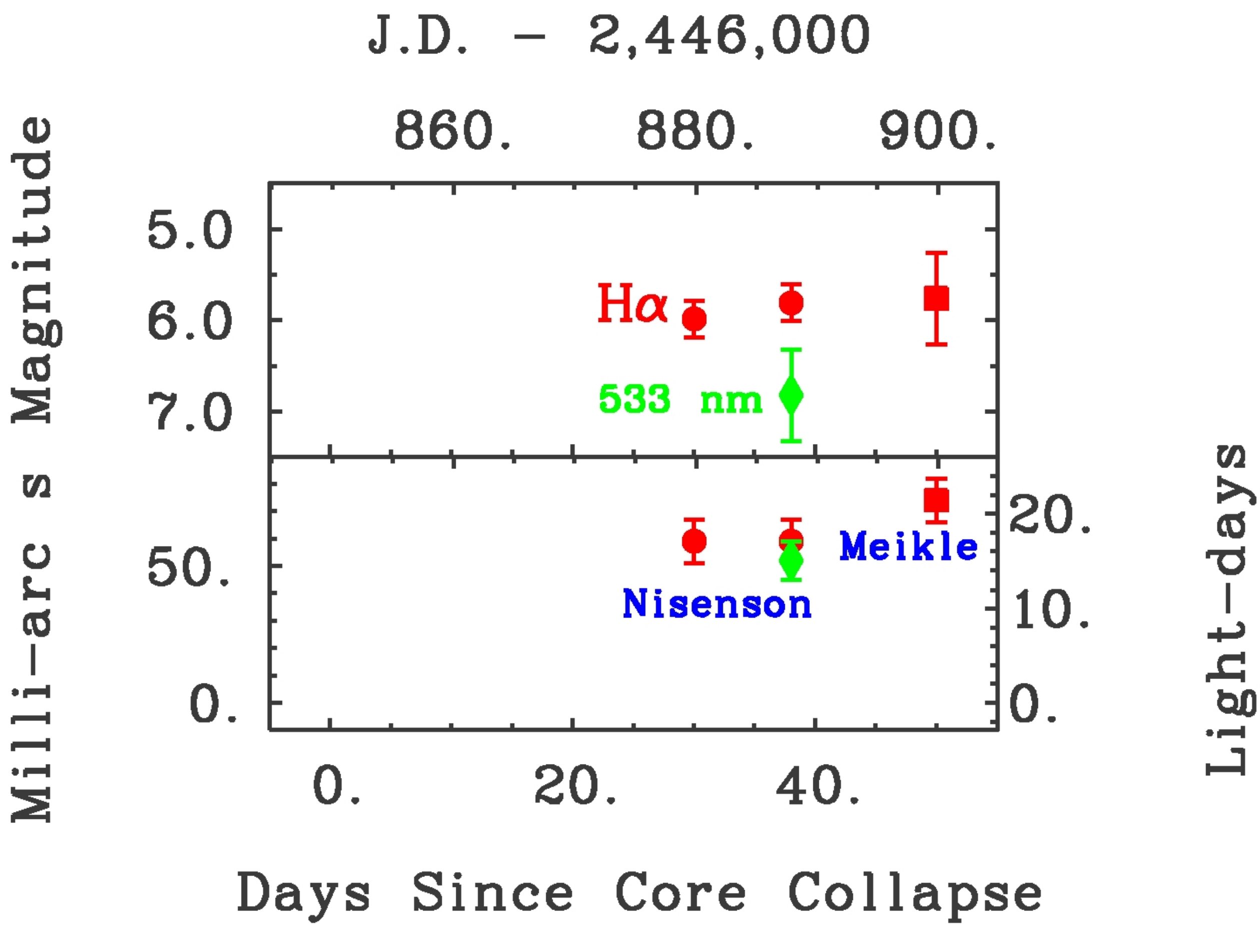

Fig. 2. Measurements of displacement (lower) and observed magnitude (upper) of the “Mystery Spot” (MS) from SN 1987A, at Hα and 533 nm, vs time, from Nisenson et al. 1987, ApJ, 320, L15, and Meikle et al. 1987, Nature, 329, 608.

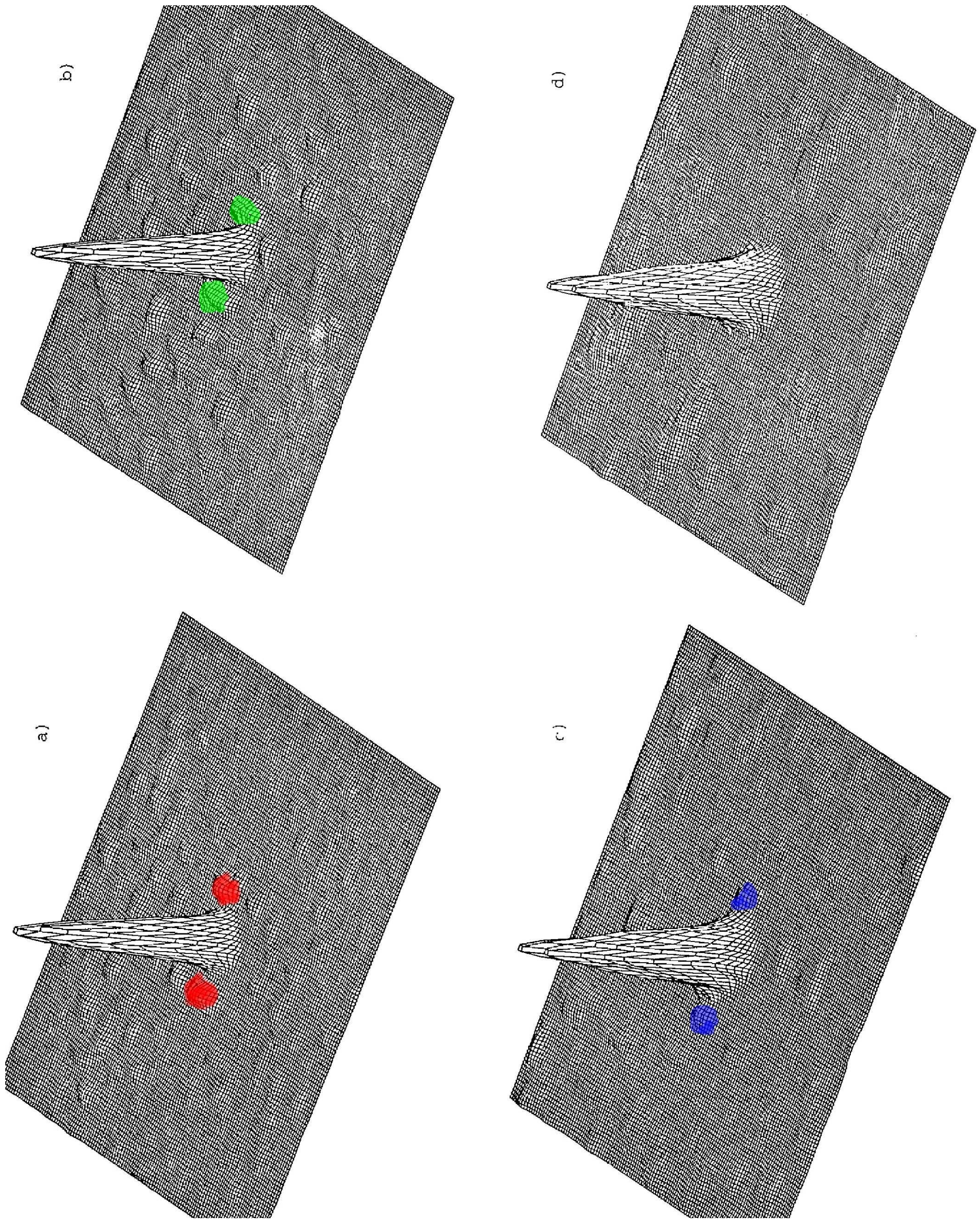

Fig. 3. From Nisenson et al. 1987, ApJ, 320, L15, SN 1987A and the "Mystery Spot" (a – lower left) in Hα (the 180^{o} ambiguity is an artifact of the reconstruction technique), (b – upper left) 533 nm, (c – lower right) 450 nm, and (d – upper right) comparison star, ν Doradus. This feature was seen 30, 38, and 50 days *after* core-collapse, with an associated total energy of 10^{49} ergs, of which some 3% was eventually radiated into the optical.

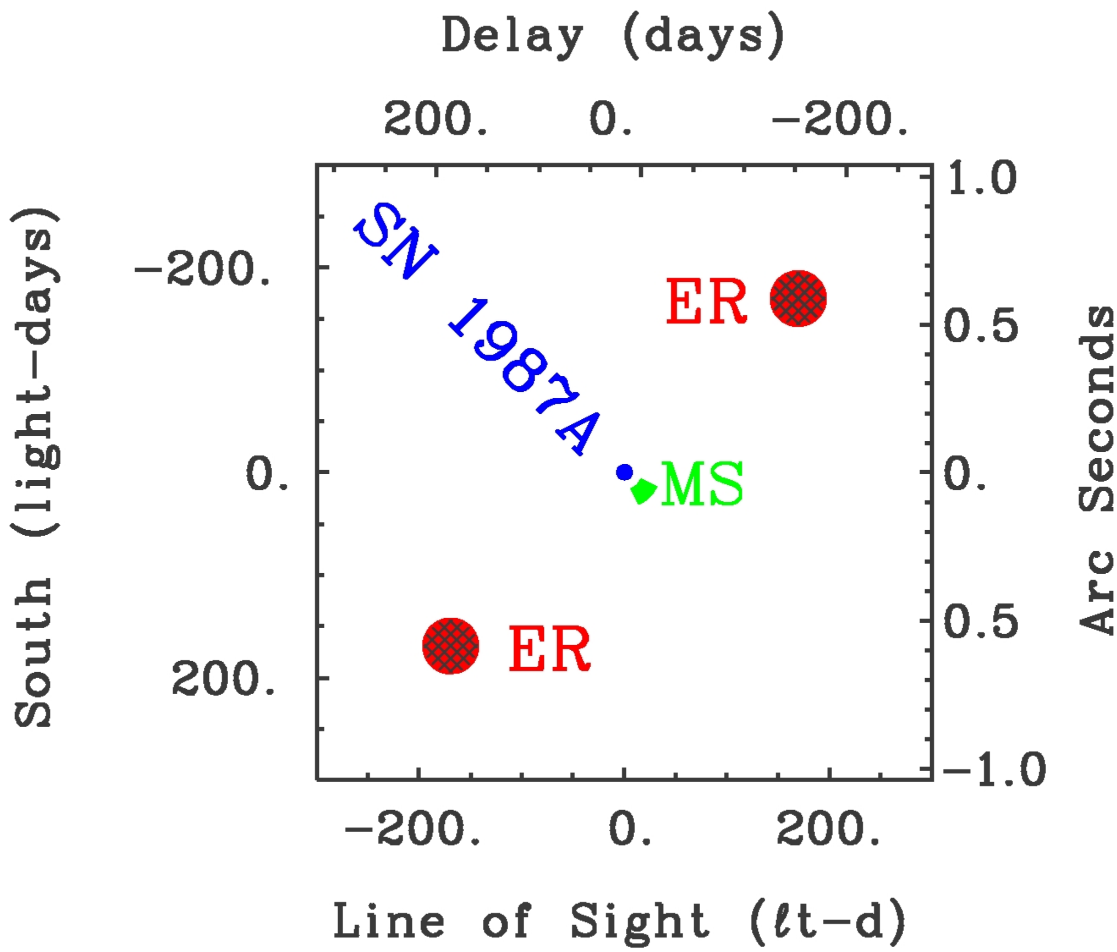

Fig. 4. The approximate geometry of the “Mystery Spot” (MS) relative to SN 1987A and the equatorial ring (ER -- shown in cross-section).

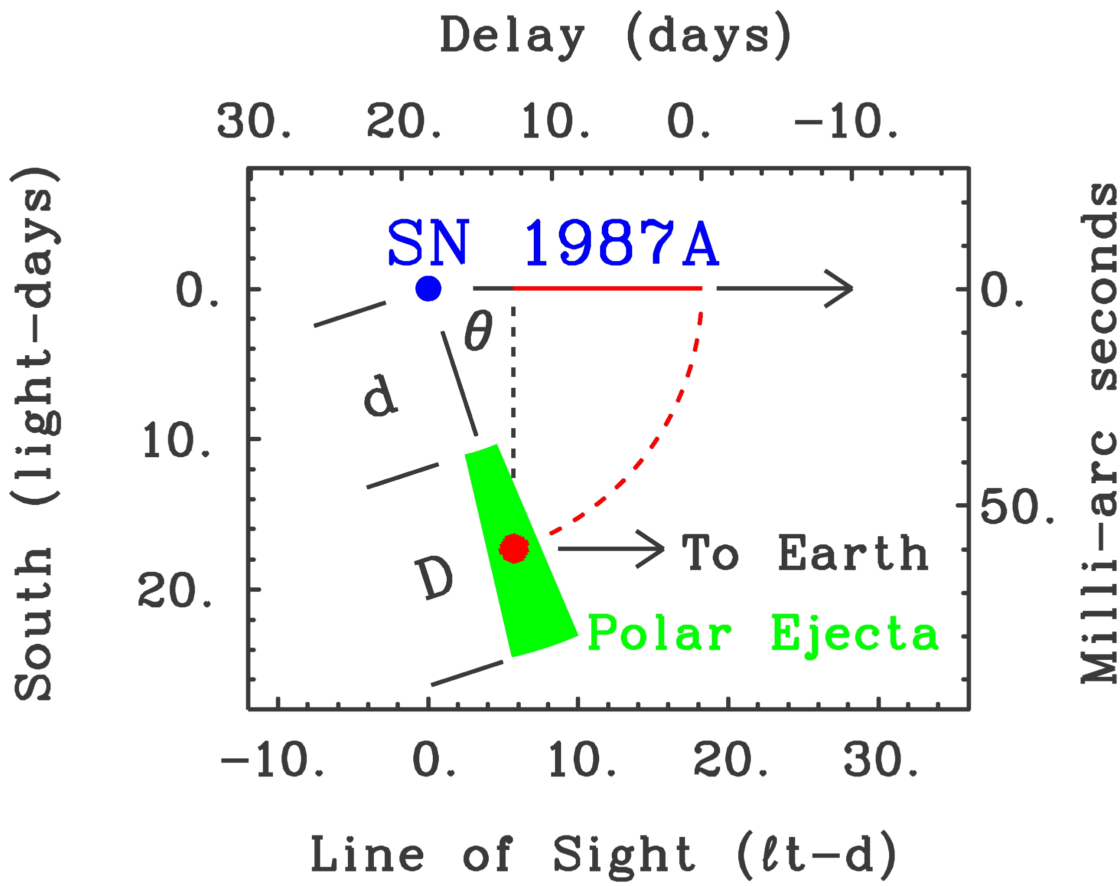

Fig. 5. The geometry of the "Mystery Spot," (MS – red dot) associated beam/jet, and direct line of sight from SN 1987A. It takes an extra *eight* days for light from 87A to hit the Polar Ejecta (PE), and proceed on to the Earth. The distance from 87A to the MS, at day 30, is ~20 light-days. An offset by the 0.5^{o} collimation angle of a GRB over this distance would delay the flux by about 100 s, the characteristic delay for long duration, soft spectrum GRBs (lGRBs).

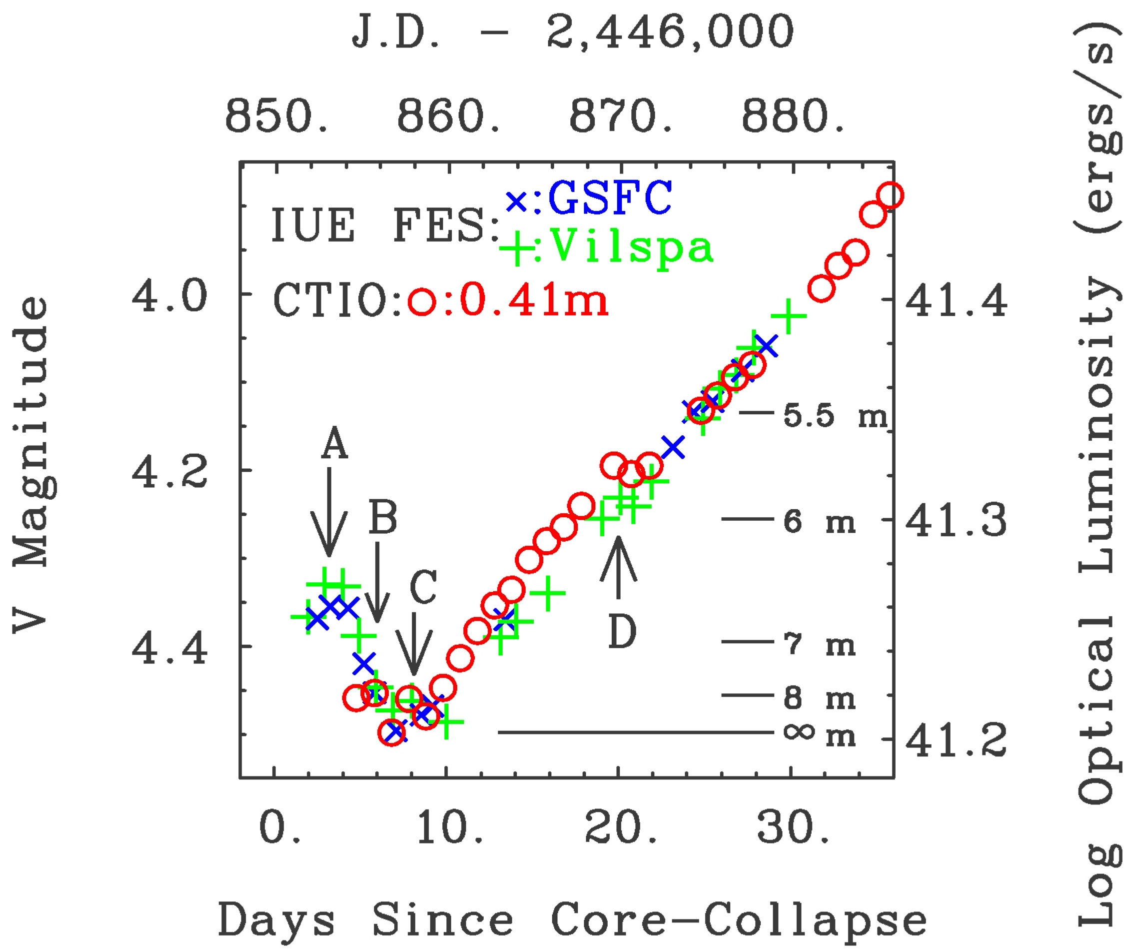

Fig. 6. After Hamuy & Suntzeff 1990, AJ, 99, 1146, and Wamsteker et al.1987, A&A, 177 L21, the very early luminosity history of SN 1987A as observed with the CTIO 0.41-m and the Fine Error Sensor of IUE. Data taken at Goddard Space Flight Center by Sonneborn & Kirshner, and the Villafranca Station in Madrid, Spain, are marked as blue x's, and green +'s, respectively. Various stages of beam/jet breakout and interaction with polar ejecta are labeled. The flux level near day 20 corresponds to 5.8 magnitudes above the day 7 minimum, the *same* (see Fig. 2) as that of the MS in Hα measured nears days 30, 38, and 50.

By using the constraints shown in Figs. 2 & 6, we can solve for the three geometric variables, d, D, and θ, diagrammed in Fig. 5, and the maximum velocity of the particles in the beam, β_{max}. First, we have the UV flash hitting the beginning of the Polar Ejecta (PE) at day 7.8 in Fig. 5:

$$d\ (1 - \cos(\theta)) = c\ t_0 == 7.8 \text{ light-days } (\ell\text{t-d}), \qquad (1)$$

where c is the speed of light. From Fig. 5 we also have the particles well into the polar ejecta by day 9.8. So we extrapolate backward at bit, and have the fastest beam particles hitting the PE at day 9.0:

$$d\ (1/\beta_{max} - \cos(\theta)\ ) = c\ t_1 == 9.0\ \ell\text{t-d}. \qquad (2)$$

Next, we have the projected offset of 0.060 milli-arc s (mas) for the Mystery Spot (MS) measured at day 29.8 by Nisenson et al. (1987). This is more difficult to pin down, but we'll assume it's in the middle of the PE and hope for a self-consistent solution:

$$(d + D/2)\ \sin(\theta) = c\ t_2 == 17.327\ \ell\text{t-d}, \qquad (3)$$

using 50 kiloparsecs (163,000 lt-years) kpc for the distance to SN 1987A (in the Large Magellanic Cloud – LMC). Finally, we have the decrement in the light curve at day 20, shown in Fig. 6, which we will interpret as the fastest particles in the jet breaking out of the PE:

$$(d + D)\ (1/\beta max - \cos(\theta)) = c\ t3 == 20\ \ell\text{t-d}. \qquad (4)$$

Solving, we get:

$$\theta = 2 \tan^{-1}[t_0 (1 + t_3/t_1)/(2t_2)] = 71.905^o, \quad (5)$$

$$d = c\, t_0/(1 - \cos(\theta)) = 11.314\ \ell t\text{-d}, \quad (6)$$

$$D = c(t_3 - t_1)/[1 + c(t_1 - t_0)/d - \cos(\theta)] = 13.828\ \ell t\text{-d}, \quad (7)$$

and

$$\beta_{max} = 1/[(t_1 - t_0)/d + 1] = 0.9041. \quad (8)$$

Can the angle of SN 1987A's bipolarity really be 72^o? This would mean that the angle between the bipolarity and the normal to the plane of the equatorial ring (ER) is quite large, some 30^o, too much for any possible spin-orbit misalignment of the binary merger that produced SN 1987A. To investigate this, we contour plottred the 2005 November 19 HST ACS data from SN 1987A (Fig. 7 immediately below):

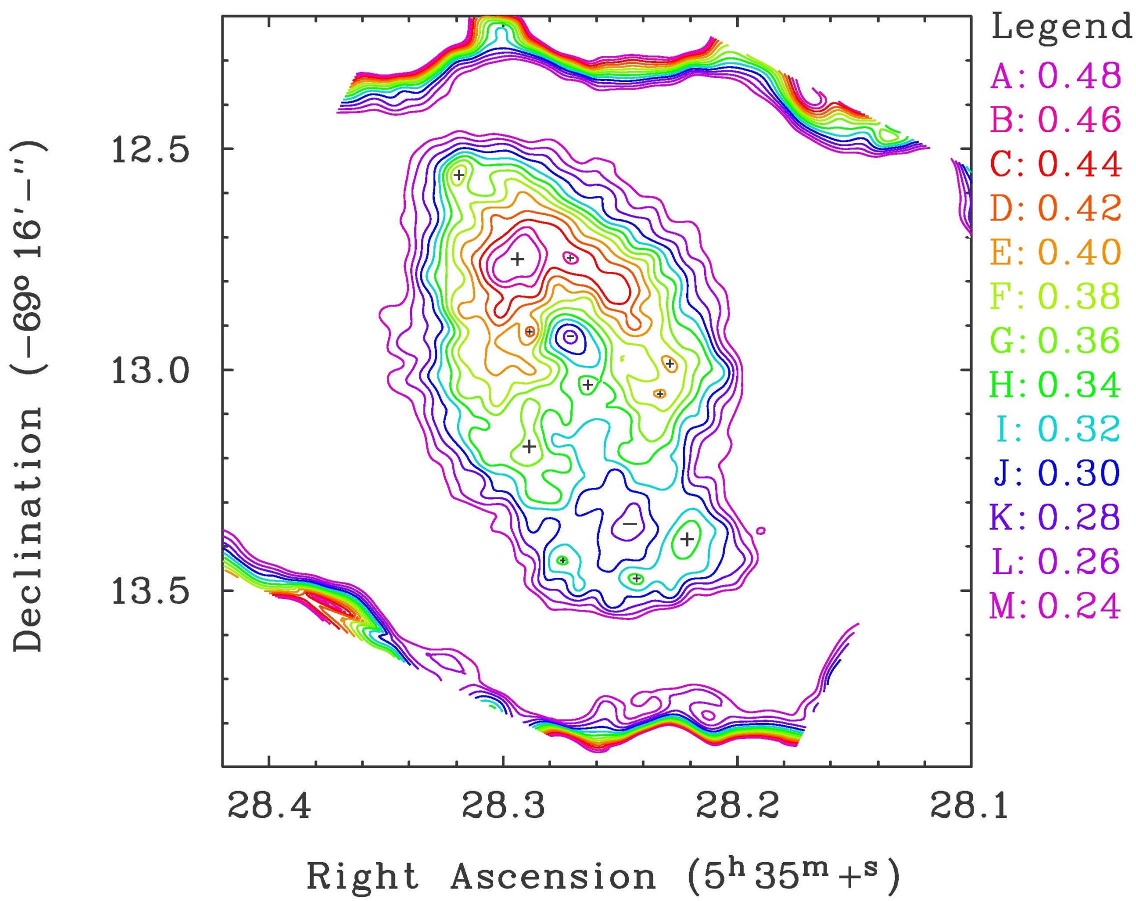

Figure 7: SN 1987A as seen by the HST ACS through the LP F8110W filter on 2005 November 19 (the equatorial ring structure outside has been cropped). The hollows in the central homunculus indicate that the polar cones are optical thin in the I band. In particular, the hollow on the upper left is the receding cone, and its hollow is clearly visible, consistent with the 72^{o} angle of the bipolarity to the line of sight derived above. The following figures sketch the sequence of events which produced the early light curve of SN 1987A.

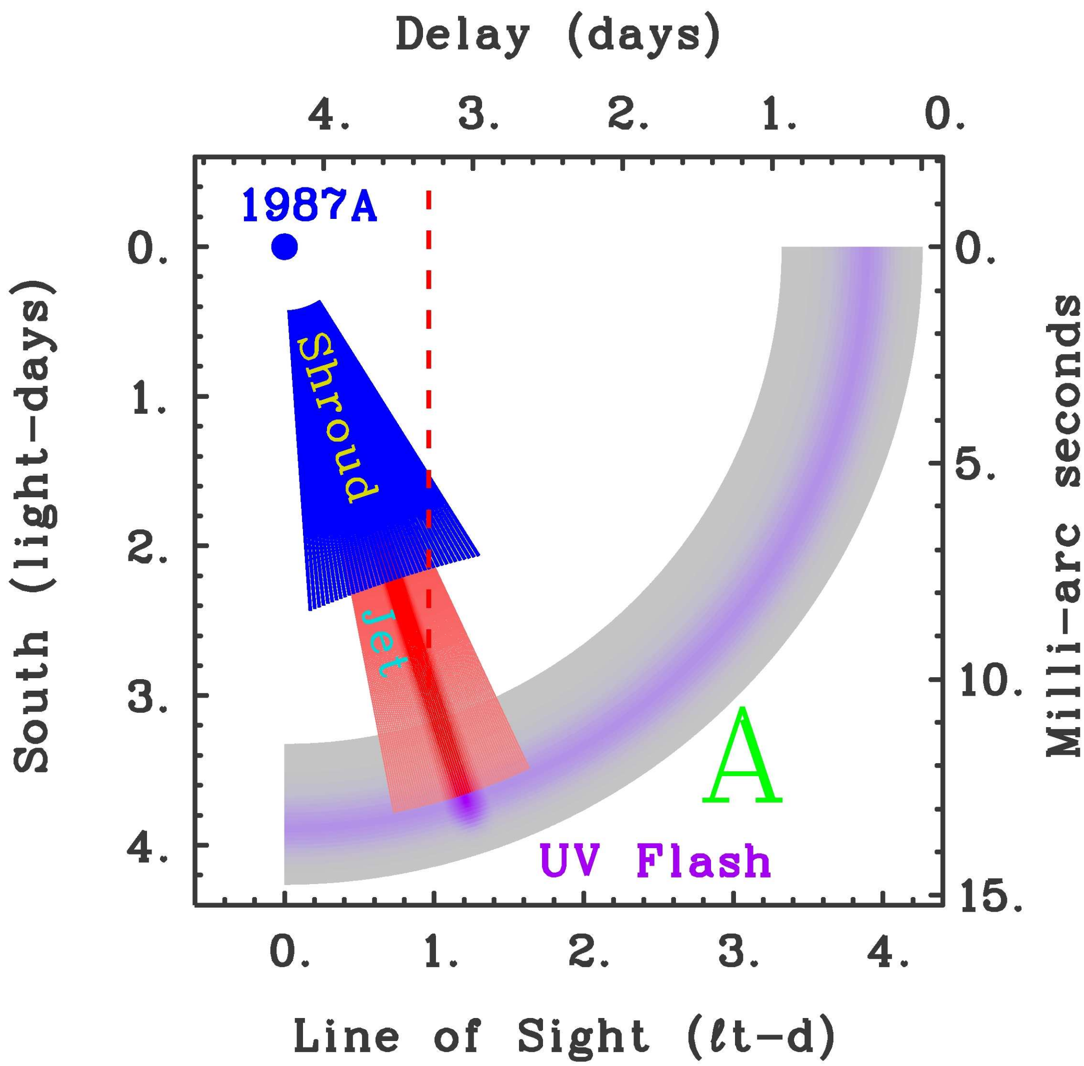

Fig. 8. The geometry of the 87A glowing beam/jet (BJ), initially opaque shroud, and UV Flash (which may have an enhanced beam of its own in the jet direction (here 72^{o}, down and to the right). The center of the emerging jet produces the rising luminosity shown in Fig. 6 at day 2 (read on the upper, delay scale). The maximum velocity of the jet is 0.9 c, that of the shroud, was arbitrarily set to 0.55 c. Because of the short time response of the luminosity shown in Fig. 6 full angular width of the jet has been set to 1.44^{o}.

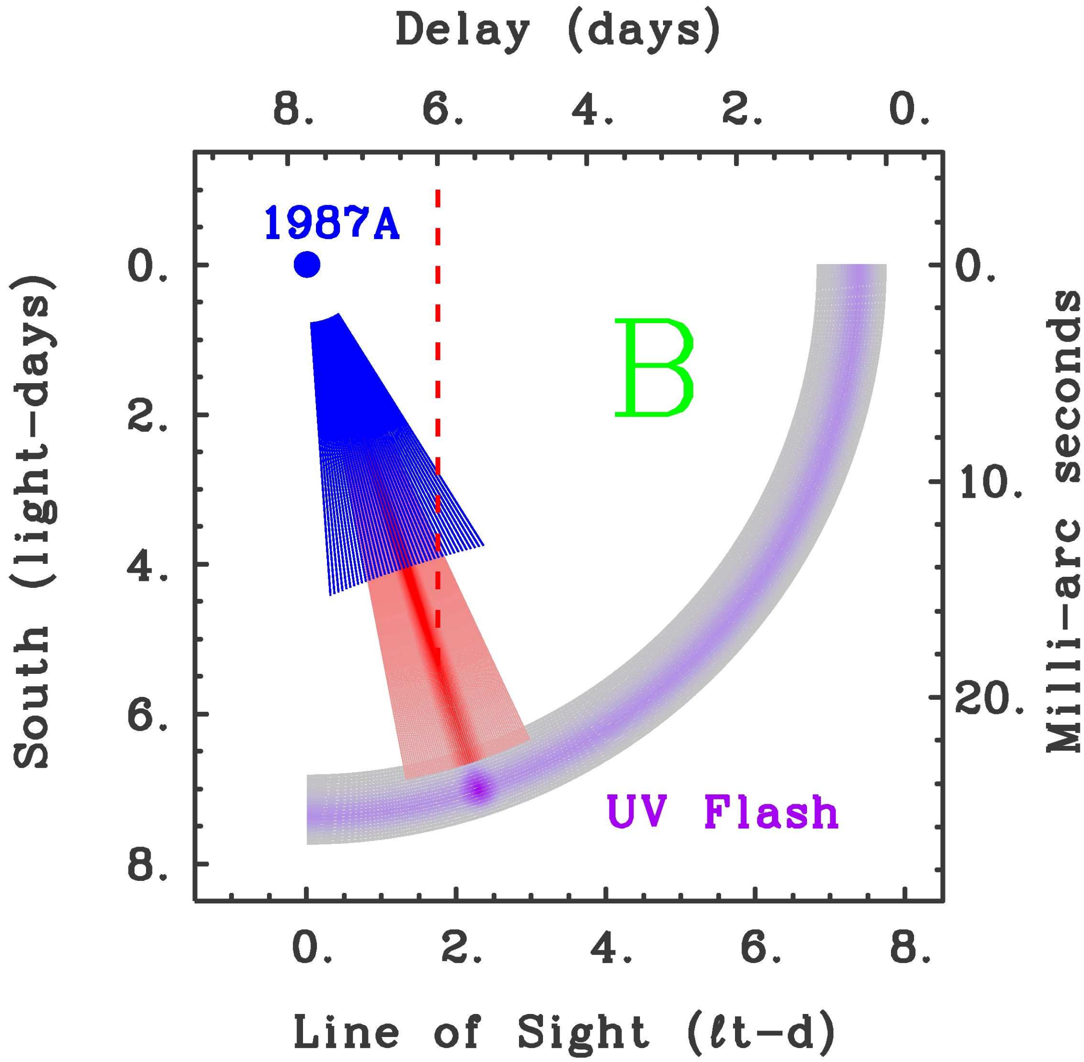

Fig. 9. The configuration in which the light from the center of the exposed part of the now fading jet lies on the dropping luminosity curve at day 6 (point 'B' in Fig. 6).

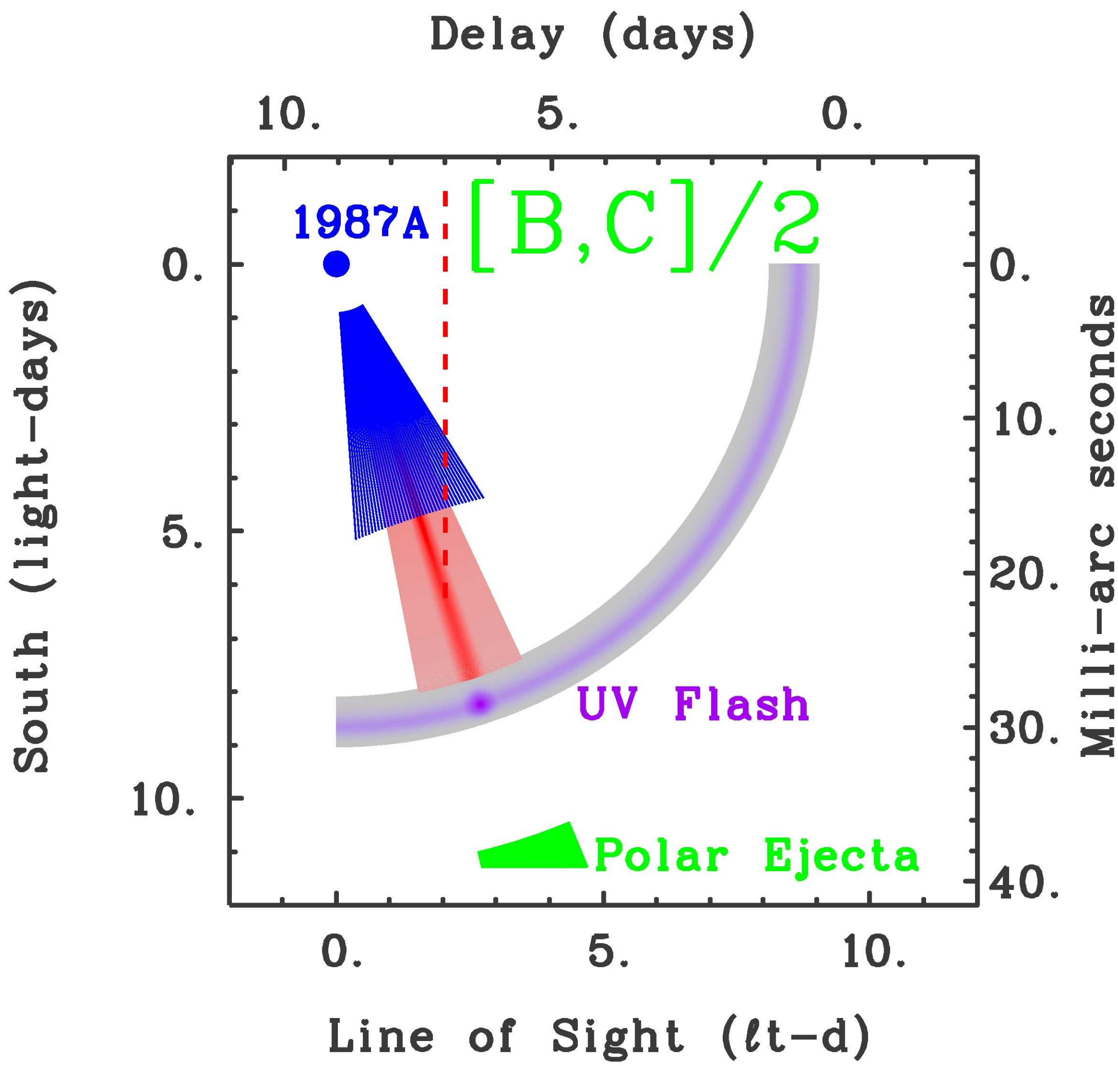

Fig.10. The configuration in which the light from the center of the exposed part of the still fading jet lies near the minimum of luminosity curve near day 7 (between ‘B’ and ‘C’ in Fig. 6).

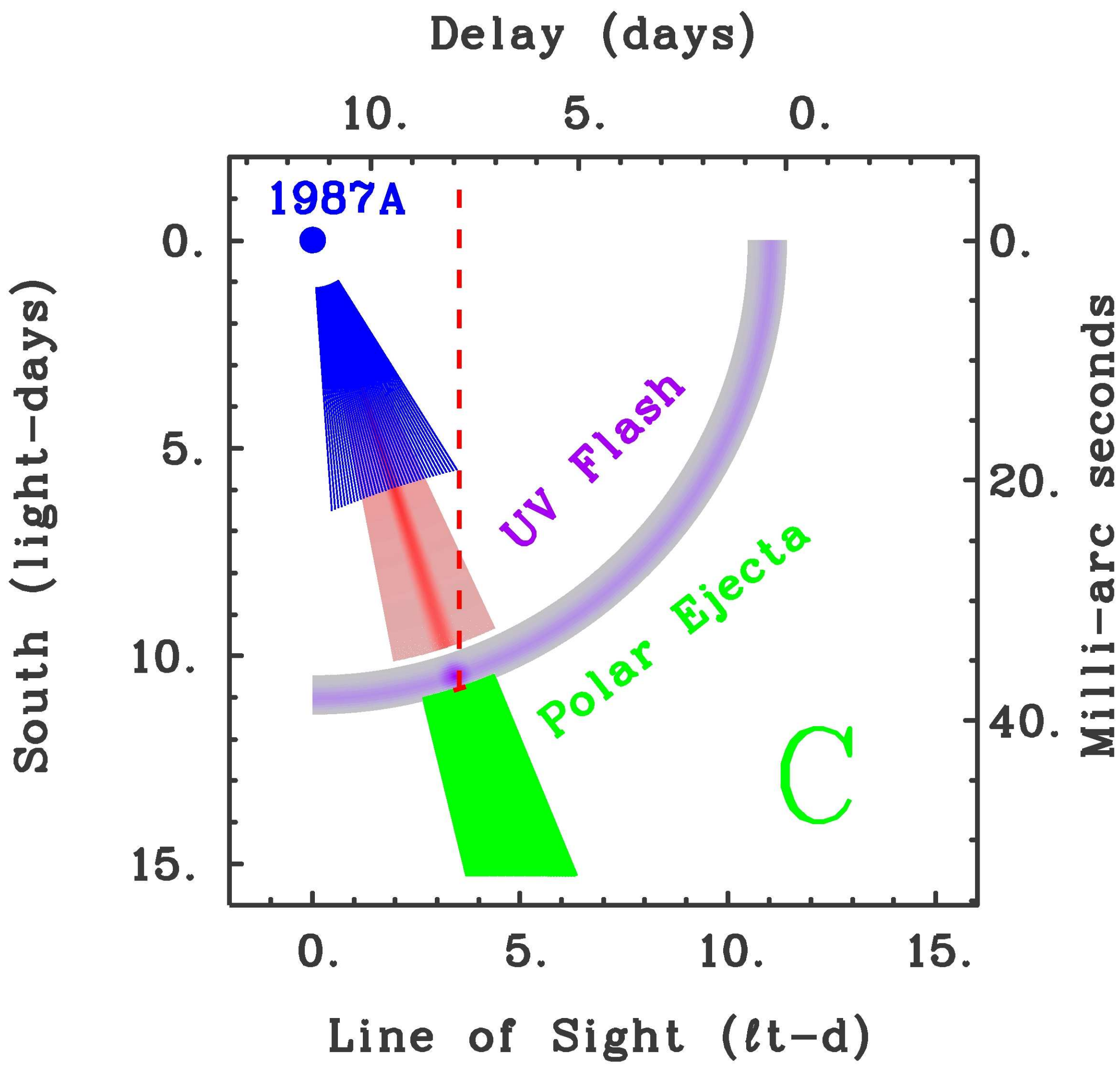

Fig. 11. The intense beam of the UV Flash scatters and reprocesses off the polar ejecta (PE), producing the jump in luminosity at day 7.8 (top scale for the tiny red disk in the PE and 'C' in Fig. 6 – ~2×10^{39} ergs/s for a day). A polar ejecta density of 10^{7} cm^{-3} would predict that the UV Flash does not penetrate it deeply, and this is confirmed by the dropoff of luminosity near day 9 in Fig. 6. The tiny red disk corresponds to the highly collimated (~1^{o}) intense beam of the UV Flash, and can not be much larger all because of the fast rise/drop in luminosity before/after day 8 in Fig. 6, and thus its collimation factor is $>10^{4}$.

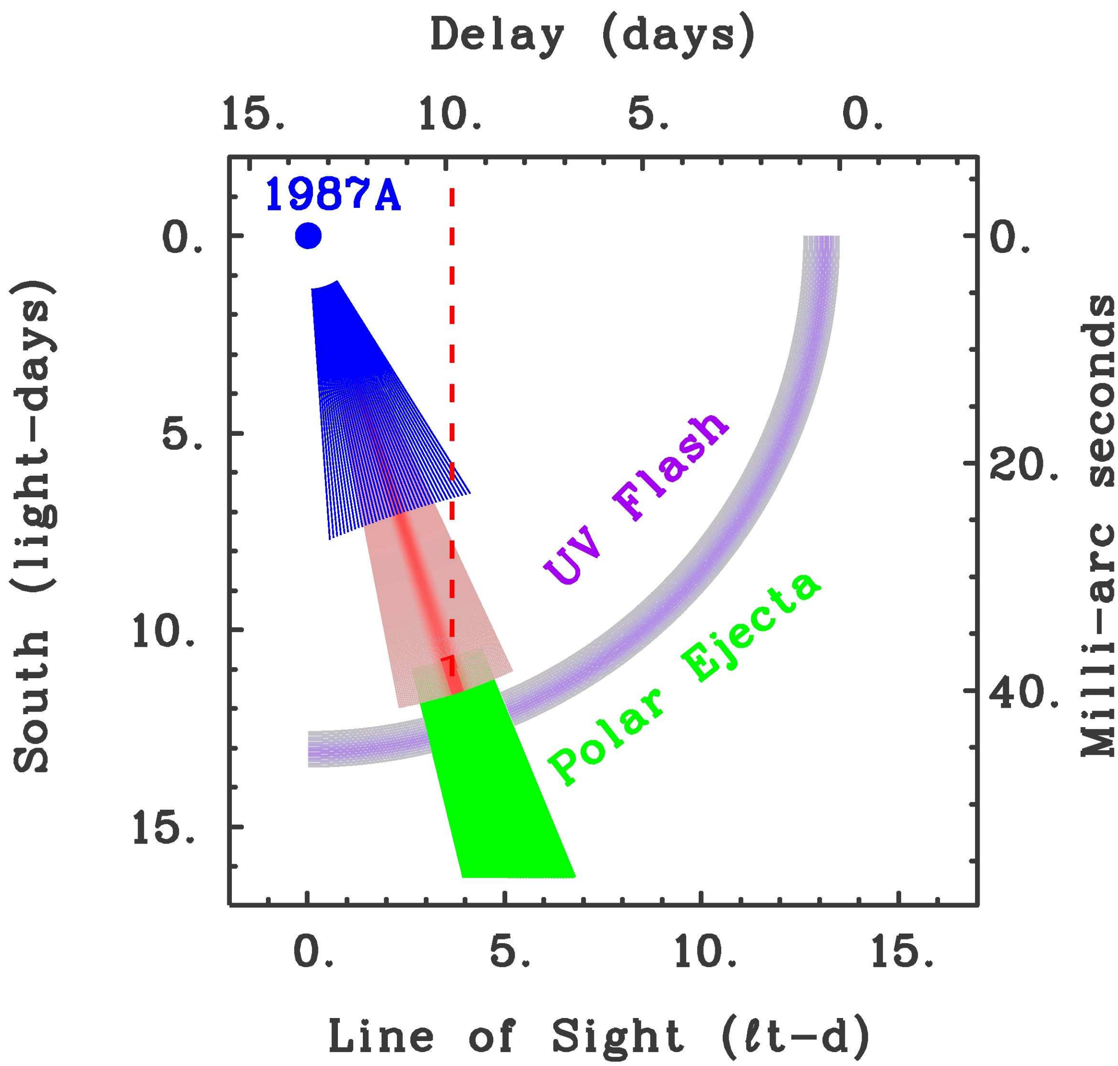

Fig. 12. The intense center (~1°) of the jet begins to produce light (red) as it penetrates into the polar ejecta (green), producing the jump in luminosity at day 9.8 (again, top scale for the red spot in this figure [12]), visible in Fig. 6 for the same time. The penetration may continue because the cross sections for this process are orders of magnitude smaller than for the UV Flash. The 0.060″ offset of the spot corresponds (loosely) to measurement of the "Mystery Spot" shown in Figs. 2, 3, 4, and 5. The collimation factor for the jet is also $>10^4$.

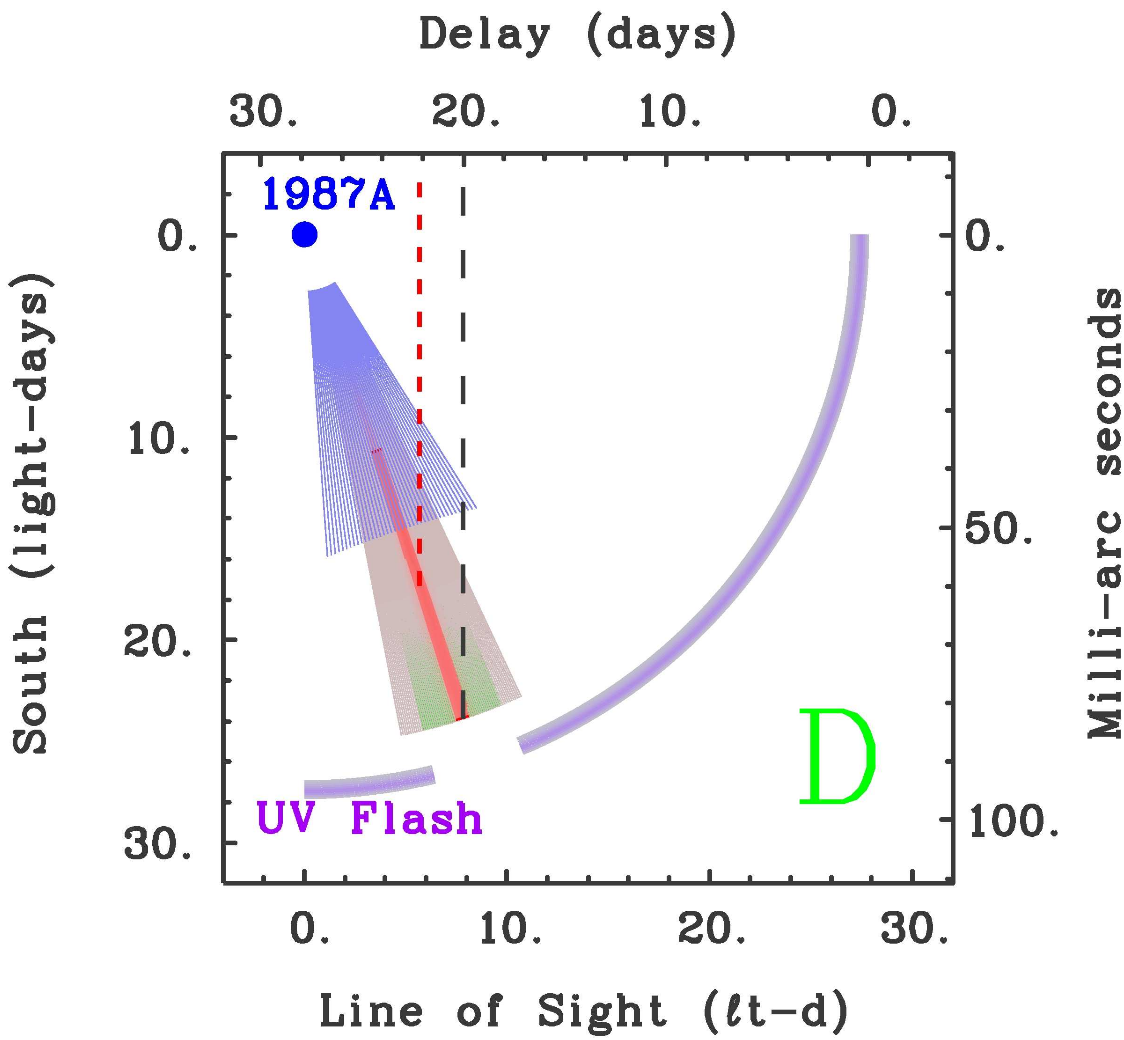

Fig. 13. Particles in the jet continue to impact the polar ejecta (mostly hidden green disk), continuing the ramp in luminosity visible in Fig. 6 near day 20 (top scale for the red strip in *this* figure [13]). By this time the rise from the 87A photosphere proper begins to contribute to the overall luminosity. Thus the MS luminosity can amount to no more than ~5×10^{40} ergs/s, or magnitude 5.8 (see Fig. 6), about 23% of the total optical flux of 2.1×10^{41} ergs/s at day 20. A lifetime of 6×10^{6} s yields the MS total optical output of 3×10^{47} ergs. A luminosity decrement, possibly indicating particles clearing the PE, appears in Fig. 6 just after this time (black, dashed line to top scale).

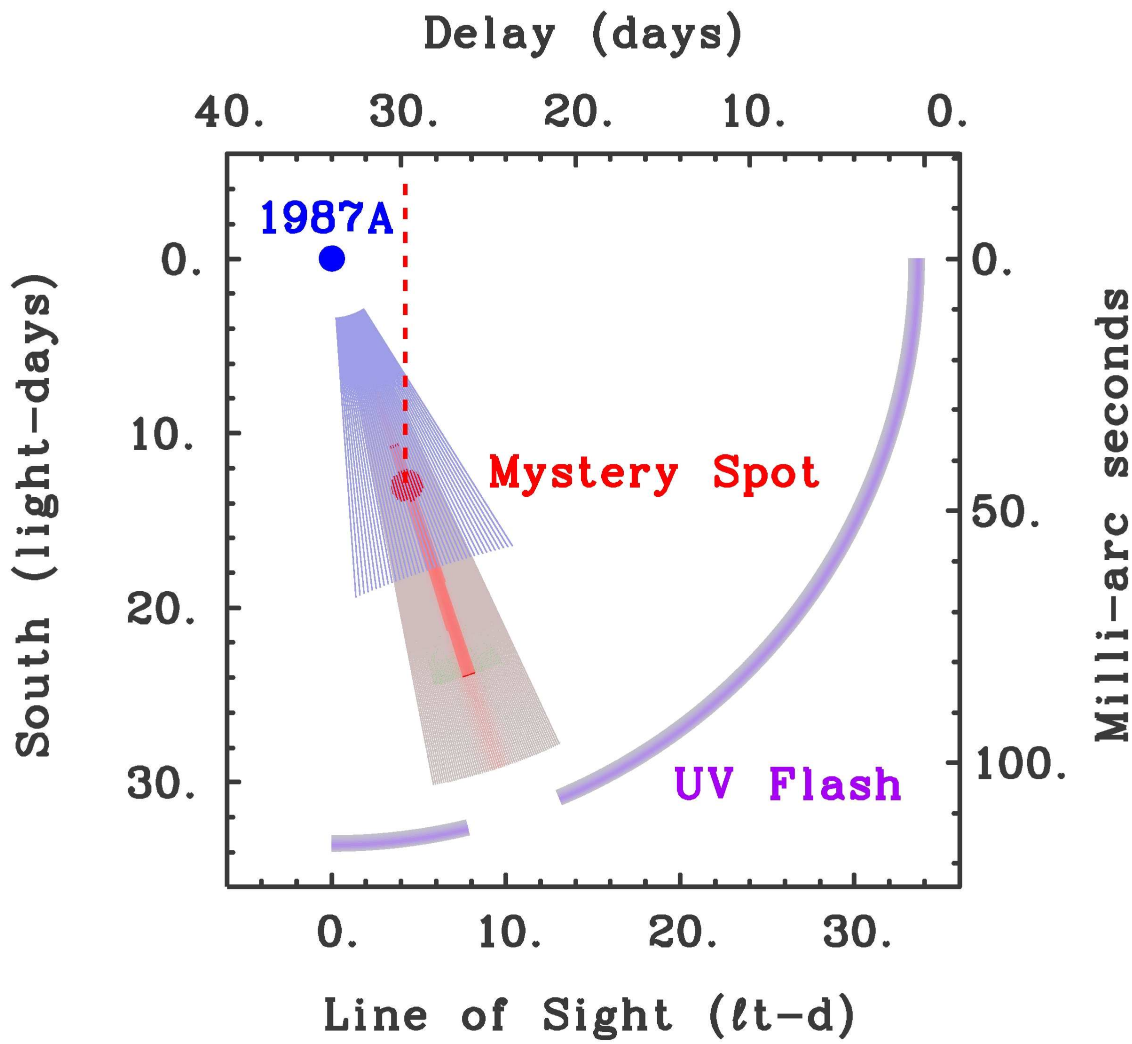

Fig. 14. Particles continue to inject energy into the Mystery Spot around day 30, where its offset from SN 1987A was 0.045 arc s. Rather than a luminous strip, the MS has become a *more spherical plume*. Penetration into a very deep (~13-14 light-days) polar ejecta is consistent MS offset measures plotted in Fig. 2. There is no hard limit on its width at this late stage, other than the widths inferred from Fig. 3.

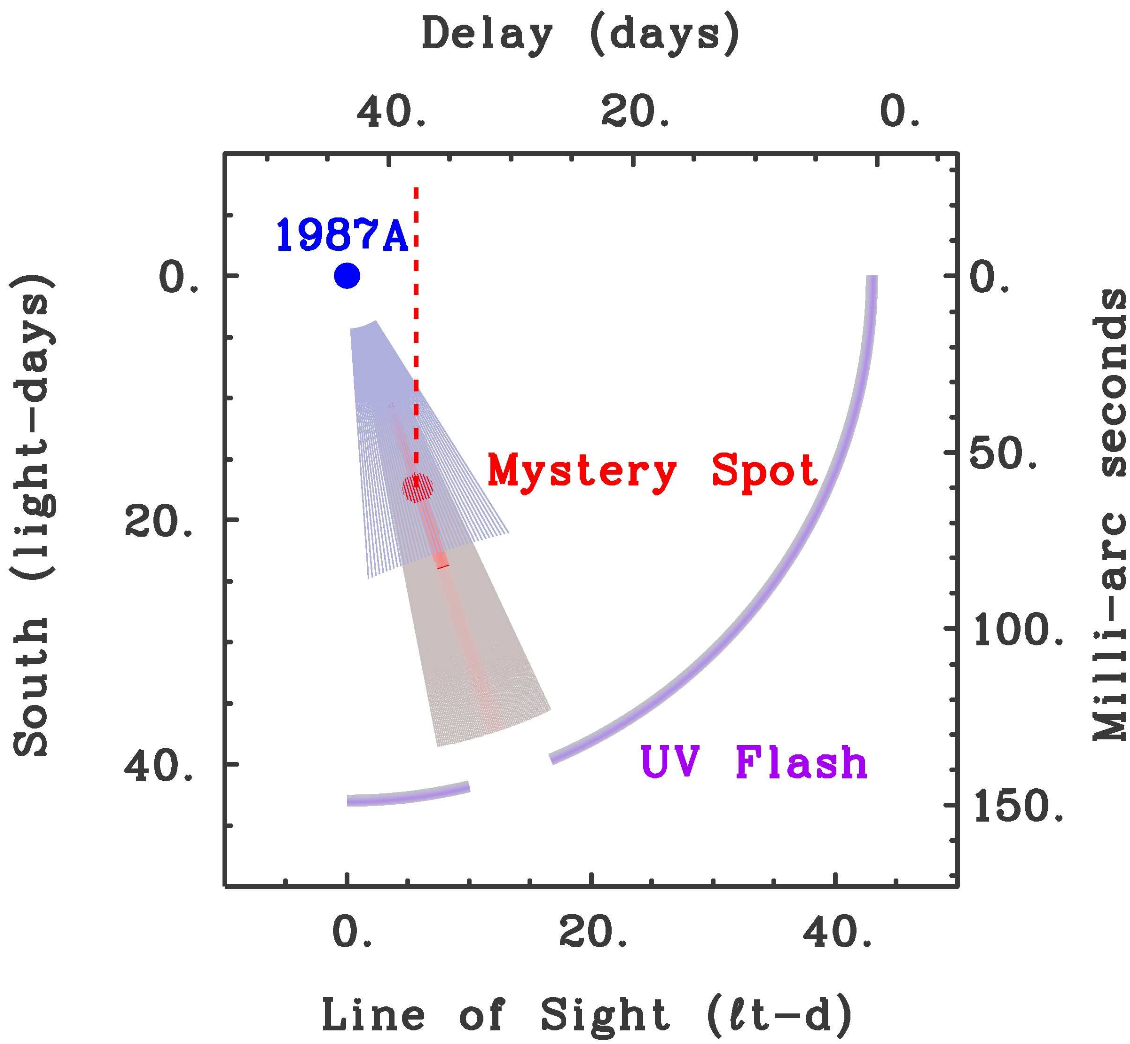

Fig. 15. Particles continue to inject energy into the Mystery Spot around day 38, where its offset from SN 1987A was 0.060 arc s. The implied velocity of the MS between this frame and the previous is ~0.5 c. It is hard to reconcile acceleration of the MS to 0.5 c at this late date with just an impulsive event at core-collapse. It is more likely that continued input of 0.5 c particles from the pulsar, similar to that seen in the Crab pulsar, is partly responsible for the acceleration.

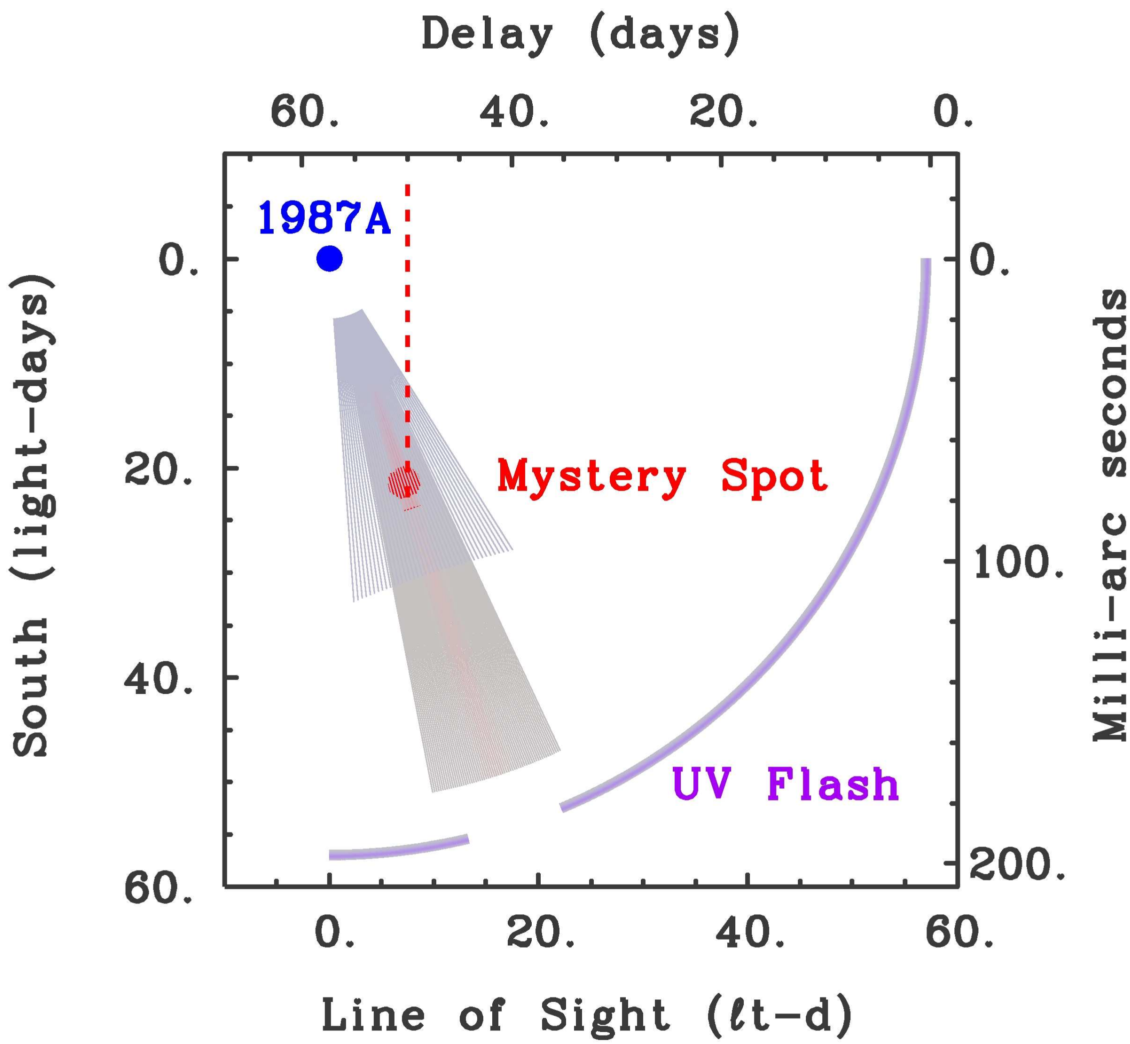

Fig. 16. Particles continue to inject energy into the Mystery Spot around day 50, where its offset from SN 1987A was 74 mas. The implied velocity of the MS between this frame and the previous is ~0.33 c. All 3 projected measured offsets (0.045, 0.060, and 0.074 arc s) of the MS at days 30, 38, and 50, lie within the bounds of the solution for the PE derived from Eqns. 1-4, by at least 2.5 ℓt-d, satisfying the self-consistent requirements.

How does all this happen?

The pulsar literally blows out the poles of all supernovae that have ever been observed, which is pretty impressive. One way this might happen is that pulsar emission may be caused by superluminal polarization currents generated outside the light cylinder, by the electric field induced from the rotating magnetic field (start with H. Ardavan 1998, Phys. Rev. E., 58, 6659, and proceed toward the present). Such polarization currents produce emission which is focused temporily at the observer's location, i.e., there are contributions from more than just a single spot. The farther outside of the light cylinder the emission (hence plasma) is, the more nearly vertical the beamed pulsation is, which at once suggests this mechanism for the SN 1987A beam/jet, as well as for gamma-ray bursts. A simple example is plotted in the following figure (17).

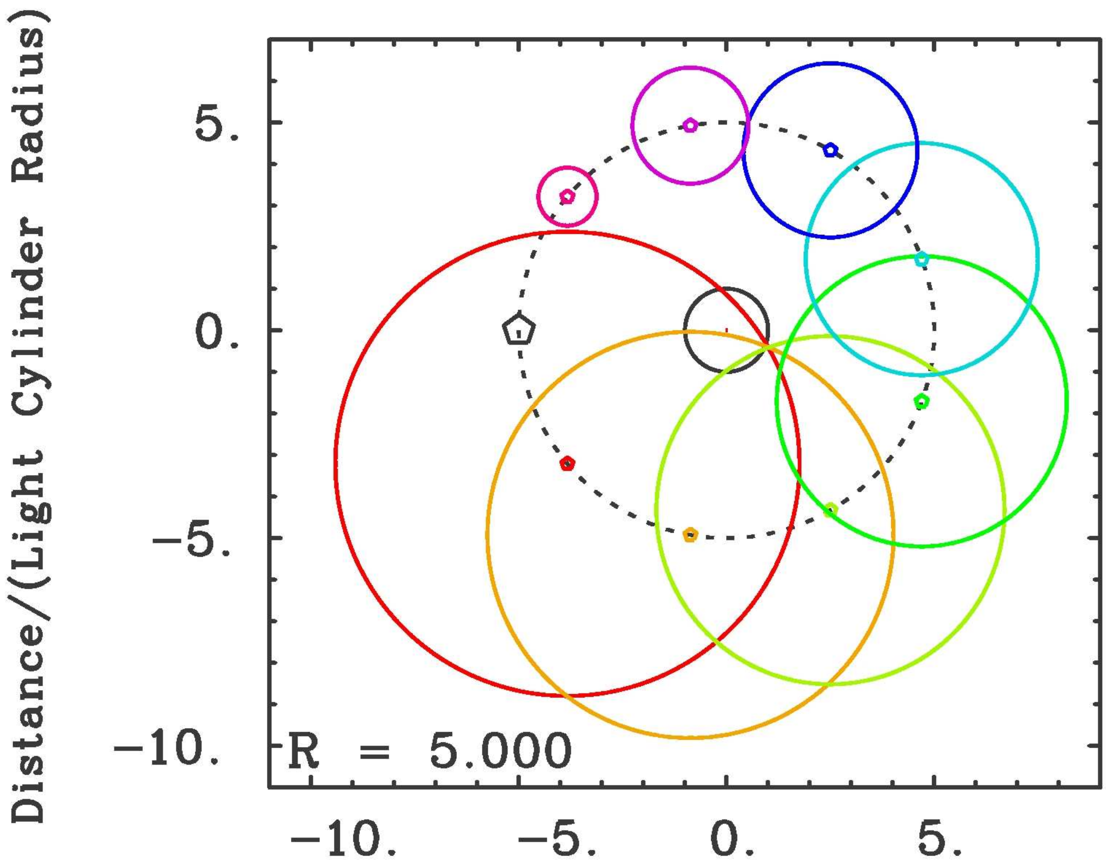

Fig. 17. Huygens wavefronts from 9 points orbiting counter-clockwise on the dashed circle, whose radius is five times that of the light cylinder (solid line, small inner circle). Superluminal polarization currents on the outer circle between 5 o'clock and 7:40 contribute to the emission tangent to the inner circle near 4 o'clock. This pulsed emission propagates with time at an angle >70^{o} to the orbital plane.

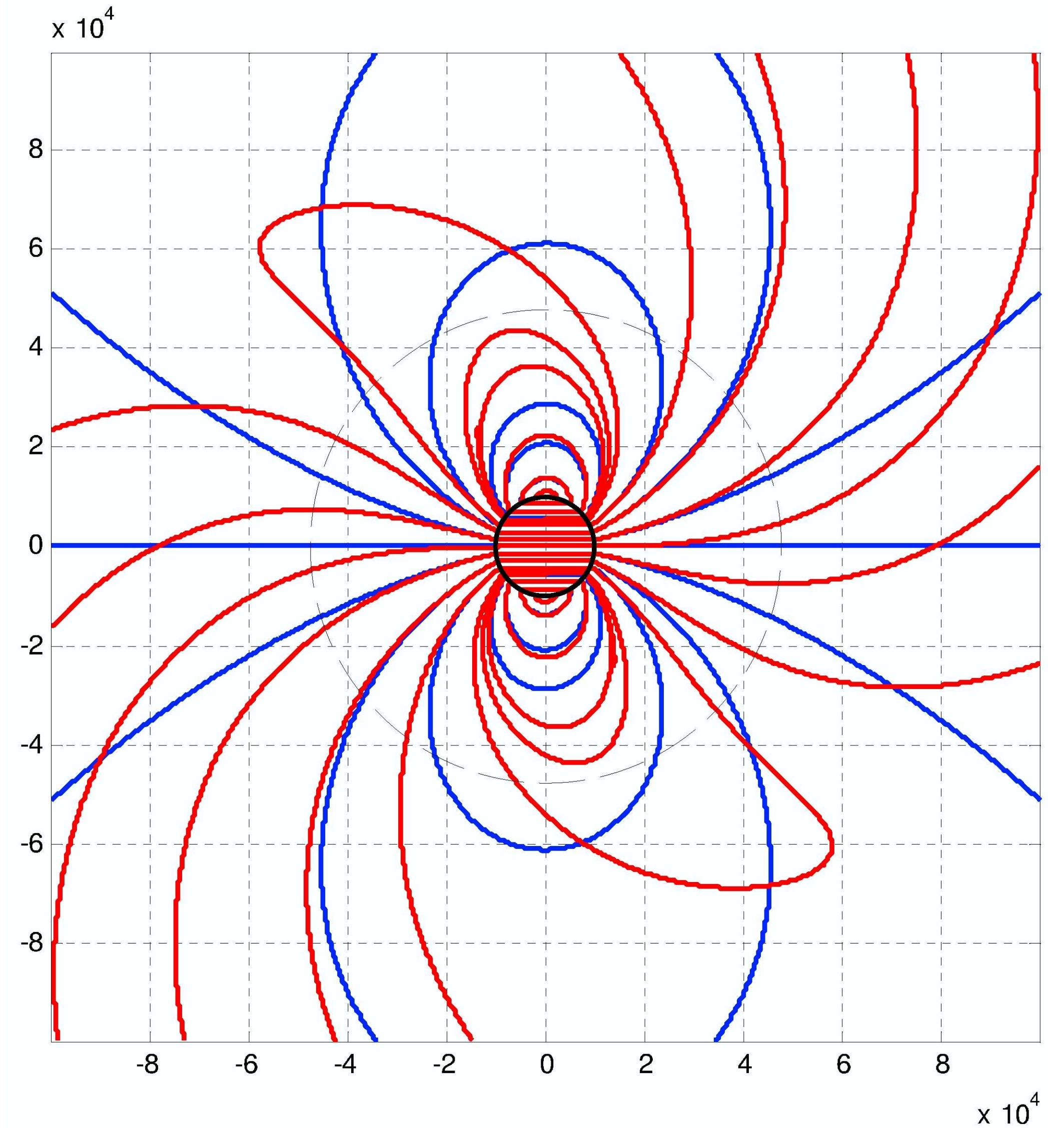

Fig. 18. Magnetic field lines are plotted for a static magnetized sphere (blue lines), and a rotating magnetized sphere (red lines). The dashed black circle represents the light cylinder, and the sense of rotation is clockwise. The small black circle represents the sphere. For a neutron star, the geometry would correspond to a rotation period of 1 ms. (From Petr Volegov, and also published in Phys. Rev. in the late 50's.)

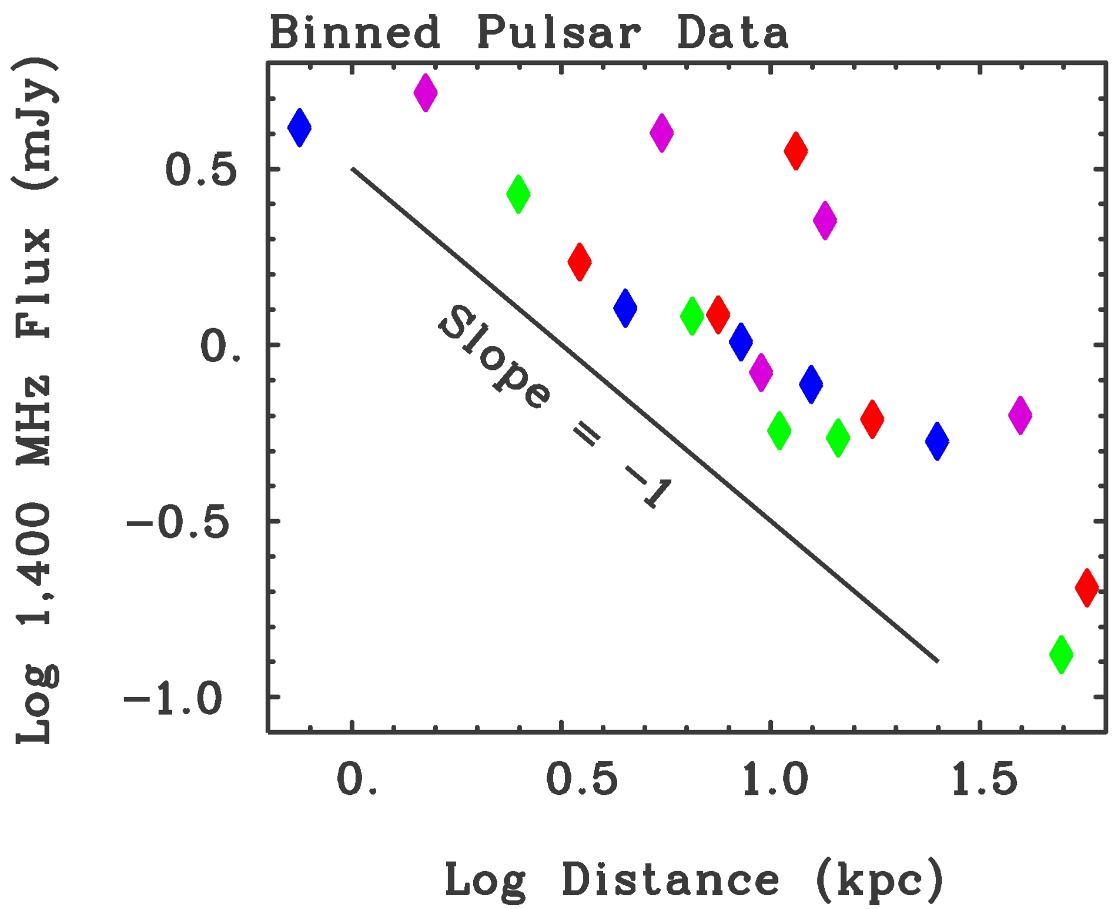

Fig. 19. (Mario's plot) The radio spectral intensities of ~1300 pulsars at 1,400 MHz, averaged into distance bins, is plotted against the central distance of the bins. That pulsar intensities dim only as 1/distance is a prediction of the superluminal polarization current model of H. Ardavan & Co.

Conclusions

The early light curve of SN 1987A indicates a beam/jet was formed at core-collapse, with the fastest particles in the jet traveling at 0.9 c. The collimation factors for its beam and jet, which produced the “Mystery Spot,” both likely exceed 10^4. The angle made by the jet to the Earth’s line of sight was 72^o, and thus the angle between its beam/jet and the normal to the plane of the equatorial ring is ~30^o. The distance from SN 1987A to the polar ejecta, in the beam/jet direction, is 11.3 ℓt-d, while its depth is 13.8 ℓt-d. The pulsations from the neutron stars, born within at least 99.98% of supernovae, blow out their envelopes in two ~polar directions, and drive GRBs. Pulsar intensities drop only as 1/R, consistent with H. Ardavan’s superluminal polarization current model (pulsar cosmology!).
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